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The Use of Adaptive Structures in Reducing Drag of Underwater Vehicles

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ABSTRACT: Experimental and theoretical studies by researchers in several countries over the last 30 years have shown that the generation of a traveling wave on the surface of a moving body may reduce drag. A laboratory-scale investigation using wave parameters identified in recent CFD studies will further understanding of the physics of traveling wave behavior. Requirements for an active wall test device are discussed in the light of previous experience and new developments in active materials and adaptive structures.

1. TRAVELING WAVE CONCEPT

The possibility of using vortical flow to reduce drag has been known for a number of years. Suitably positioned transverse slots can result in entrained vortices and a significant reduction in end drag over the closure of a bluff body. In addition, experiments at NASA Langley have shown that ordered periodic vorticity injected into a turbulent boundary layer near a wall results in about 25% drag reduction over nominal flat plate values.

A related concept in fluid flow dynamics has been investigated with a view to improving the hydrodynamic performance of underwater vehicles. A traveling wave with specified and controllable phase velocity, amplitude, wavelength and shape is used to generate and trap vortices in the troughs of a flexible wall (Figure 1). The resulting secondary flow condition cannot be classified as conventional laminar, transitional or turbulent flow, but rather constitutes a new regime described as "controlled vortical flow". Analytical studies (Wu et al., 1990) have shown that an appropriate tailoring of traveling wave to flow parameters results in ordered vortical flow and an associated reduction in drag to a level substantially below flat plate values. Further computational verification of the traveling wave concept will likely be costly, and may not engender the same level of confidence as an experimental demonstration. Thus the need for a practical investigation has been identified.

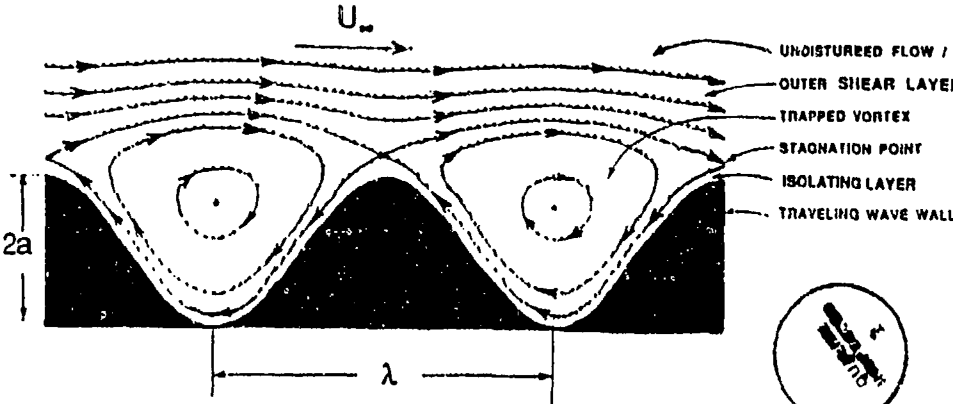

Figure 1. Elements of Traveling Wave Flow

2. PROOF-OF-CONCEPT INVESTIGATION

The principal objectives of the proposed experimental investigation of traveling wave behavior are to demonstrate vortex entrapment in the troughs of a traveling wave using flow visualization techniques, to determine the combinations of wall and flow parameters giving drag reduction, and to assess the trade-off between the energy required for wall activation and the energy gained through drag reduction.

Experimental demonstration of the traveling wave concept is a multidisciplinary problem involving aspects of hydrodynamics, materials, and control systems technologies. In particular, practical demonstration of a controlled vortical flow regime will involve the design and fabrication of some kind of flexible wall device. A traveling wave with specified parameters (see below) will be used to generate and trap vortices in the troughs of a flexible wall. An active wall is defined as one which uses energy from an external source for deformation, in contrast to a passive wall which uses energy from the flow to deform. For the purposes of the proposed proof-of-concept investigation an active wall has been identified as the more attractive option, since it offers the experimenter a high degree of control, thereby eliminating the need for extensive instrumentation to measure traveling wave parameters.

3. ACTIVE WALL TEST DEVICE

Computational fluid dynamics (CFD) studies of traveling wave behavior have shown that the amplitude-to-wavelength ratio, a/λ, and ratio of wave velocity to freestream velocity, c/U_∞, are critical parameters influencing vortex entrapment and establishment of a controlled vortical flow. Parameter ranges of interest are:

$$0.10 \leq a/\lambda \leq 0.25 \qquad (1)$$

$$c/U_\infty \approx 0.5 \qquad (2)$$

Target ranges for active wall parameters have been defined on the basis of the above values, together with information on wavelength, freestream velocity, and Reynolds number (based on wavelength) for practical applications. The need to reduce complexity and minimize costs has also been taken into account. Wavelengths (λ) should be in the range 5 to 20 cm, and the active device length (L) should incorporate at least 10 wavelengths, i.e. $L \geq 10\lambda$. Amplitudes of oscillation should be in the range 0.5 to 5 cm such that (1) is satisfied. Frequencies of 10 to 100 Hz and wave velocities of 2 to 5 $m.s^{-1}$ are required.

One of the major design goals for an active wall test device is that the wave amplitude, together with two of the three related parameters - wavelength, wave velocity and frequency - should be independently controllable. The potential to investigate various waveforms would be an added advantage. No definitive conclusions have been reached regarding the relative merits of 2-D (plate) and 3-D (axisymmetric body of revolution) devices. It has been postulated that drag measurements may be easier using a towed 3-D device, whereas investigation of ranges of wall and flow parameters and flow visualization experiments may be more readily performed using 2-D test plates.

4. PREVIOUS EXPERIENCE

A number of active wall devices have been reported in the literature over the last 20 years. The relevant articles have been reviewed in some detail in order to avoid unnecessary duplication of existing results and to benefit from the experience of previous researchers. The choice of actuator type is seen to be critical in determining traveling wave parameters, notably amplitude and frequency. The majority of devices discussed in the literature are mechanically-driven systems of the type shown schematically in Figure 2. These devices utilize a series of cams positioned on a camshaft with a successive phase difference between adjacent cams. These systems are generally fixed amplitude and wavelength devices, although frequency and wavespeed can be varied by altering the speed of rotation of the camshaft. The number of actuator elements per wavelength is important in determining the wave profile. Since the cost of any traveling wave device increases with the total number of actuators used, it is desirable to select the minimum number of driving elements to achieve the required waveform. Eight actuators per wavelength are generally believed to be necessary to achieve a satisfactory sine wave profile.

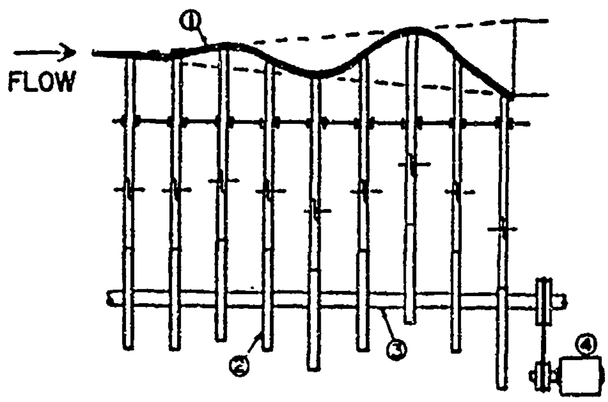

Figure 2: Schematic of Mechanically - Driven Active Wall Device
1=rubber, 2=cam, 3=camshaft, 4=motor

Most of the active wall devices described in the literature were designed for amplitude-to-wavelength ratios, a/λ, significantly lower than the desired range identified in the present CFD studies. Unfortunately, most investigators who claim to have measured a reduction in drag (or even a thrust force) using an active wall device have not documented their experiments in sufficient detail for parameter ranges to be identified unambiguously.

5. CANDIDATE ACTUATOR SYSTEMS

The active wall test device required for a traveling wave proof-of-concept experiment constitutes an adaptive structure. In order to achieve the shape control associated with traveling wave generation, actuators must be incorporated in the active wall system. The following candidate actuators have been reviewed in the light of present requirements and recent developments in active materials technology:

- mechanical
- pneumatic
- hydraulic
- piezoelectric and electrostrictor
- shape memory alloy
- electromagnetic
- magnetostrictor
- electrically conductive polymer

The requirement for wave amplitudes ≥ 0.5 cm combined with frequencies in the range 10 to 100Hz imposes severe restrictions on actuator systems, many of which are either frequency- or amplitude-limited. In general, the requirement for wavelengths on the order of 10 cm can be readily accommodated.

The frequencies of mechanically-driven active wall devices described in the technical literature are generally ≤ 30 Hz. Some difficulties may be anticipated in combining amplitudes on the order of 1 cm with frequencies greater than ~ 30 Hz and a mechanical device designed to operate under these conditions would need to be reasonably robust. Ideally, a test device would be designed such that wavespeed, amplitude and frequency could be varied independently. However, the feasibility of achieving this degree of flexibility with a mechanically-driven device has not been demonstrated to date.

Recent progress in developing shape memory alloys (SMA's), such as Nitinol, has resulted in helical actuators which can produce deformations on the order of 1 cm. However, difficulties in rapid cooling of SMA wires limit the frequency-response of state-of-the-art actuators to a few Hertz, even using active cooling. Both pneumatic and hydraulic systems are also limited to frequencies below 10 Hz.

Piezoelectric, electrostrictor and magnetostrictor actuators are all amplitude-limited (< 0.01 cm), despite recent significant enhancements in maximum strain values. An active wall device using piezoelectric ceramic actuators (PZT) has been developed (Park, Silvus and Cerwin, 1985). Amplitude, frequency and velocity of the traveling wave are all independently controllable, making this device extremely flexible in terms of parameter refinement. The use of an electronic drive system permits the generation of a traveling surface wave of arbitrary shape. However, wave amplitudes are small (≤ 13 microns), and even the use of state-of-the-art piezoelectric actuators could not produce deformations on the order of 1 cm.

The possibility of using the attractive and repulsive forces between electromagnets, or between an electromagnet and a permanent magnet, has been proposed as a means of generating a traveling wave. A device described in a Soviet Inventor's Certificate (Kim, Afonin and Bondarenko, 1972) uses damping fluid between the hull and outer skin, and a hull-mounted inductor provides a variable electromagnetic field. The purpose of the device is "to reduce the frictional drag of underwater vessels". Unfortunately, no performance data are available by which to assess the suitability of electromagnetic systems for a traveling wave proof-of-concept experiment, or for practical applications.

Electrically conductive polymers are generally made by doping of insulating polymers. Certain dopant/polymer combinations exhibit dimensional changes of up to 10% in length associated with the insulating/conducting transition. Hence, these materials may be used as actuators converting electrical to mechanical energy. However, conductive polymer actuators have not yet been sufficiently investigated to be considered serious candidates for an active wall test device.

6. CONCLUSIONS

A laboratory-scale experimental investigation has been identified as a logical next step in furthering current understanding of the physics of the traveling wave. The most cost-effective near-term option for an active wall device appears to be a mechanically-driven system with variable wavespeed and frequency, together with variable amplitude or wavelength. Such a device is expected to be noisy and cumbersome, and unsuited to underwater vehicle applications. Practical implementation of the traveling wave concept to reduce drag will likely involve significant developments in state-of-the-art active materials and adaptive structures, or the implementation of a tailored auto-oscillatory system.

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